Experimental Brain Research (2019) 237:3047–3058
https://doi.org/10.1007/s00221-019-05650-8

RESEARCH ARTICLE

Analysis of head and chest movements that correspond to gaze directions during walking

Hirotake Yamazoe[1] · Ikuhisa Mitsugami[2] · Tsukasa Okada[3] · Yasushi Yagi[3]

Received: 28 February 2019 / Accepted: 6 September 2019 / Published online: 17 September 2019

Abstract
In this paper, we analyze the relationship between head and chest movements and gaze direction in both walking and non-walking conditions. In a different approach from existing studies, we aim to analyze behavior when humans intentionally gaze at a certain target from two perspectives: (1) the relationship between gaze and body movements and (2) the effects of walking on body motion. We performed three experiments: fixed target scenes (Experiment 1), moving target scenes (Experiment 2) and more realistic gazing scenes (Experiment 3). The experimental results showed a linear relationship between the head and chest directions and gaze directions regardless of walking, non-walking situations, or target movements, and stronger gaze–head correlations than gaze–chest correlations. Further, we found effects of walking that constrained rotational body movements, and that body parts with larger moments were easily affected by walking. These results suggest that the findings of existing studies in non-walking situations may be applicable to walking situations directly or with simple modifications.

Keywords Gaze direction · Head and chest movements · Gait analysis

Introduction

We obtain visual information about the world around us by moving our eyes. To obtain a wide range of visual information, we make head movements as well as eye movements (Barnes 1979; Zangemeister and Stark 1982). Many researchers have reported that the eyes and head move cooperatively, and that there are relationships between eye and head movements (Stahl 1999; Thumser et al. 2008; Freedman and Sparks 2000; Oommen et al. 2004; Zangemeister and Stark 1982). Stahl et al. measured head and gaze directions, and reported relationships between head movement amplitude and eye movements in both experimental and natural settings (Stahl 1999; Thumser et al. 2008). Freedman et al. (2000) showed that saccade kinematics during gaze shifts with large head components can be predicted by taking into account the amplitude of the concurrent head movement. Furthermore, some research has shown coordination of the eyes and head in predictable gaze target scenes (Oommen et al. 2004; Zangemeister and Stark 1982). These studies show that the eyes and the head move cooperatively when people move their gaze directions.

When people want to look around a wider area, they tend to move not only their eyes and head but also their chest (trunk). Thus, there are also many studies that have analyzed relationships between eye, head and chest movements (Anastasopoulos et al. 2015, 2009; Sklavos et al. 2010; Fang et al. 2015). Anastasopoulos and his colleagues analyzed movements of the eyes, head and trunk, and found various relationships, such as the relative rotations of the eyes, head and trunk have only two degrees of freedom (i.e., there is coordination between the eyes, head and trunk) (Anastasopoulos et al. 2015, 2009; Sklavos et al. 2010). Fang et al. (2015) also showed that the eyes and head move cooperatively, and that the head direction biases the eye direction during visual search in a 360° display.

During walking, the eyes, head and chest also move cooperatively to stabilize gaze. There are many studies that have focused on compensatory movements of the eyes, head and

✉ Hirotake Yamazoe
yamazoe@fc.ritsumei.ac.jp

Ikuhisa Mitsugami
mitsugami@hiroshima-cu.ac.jp

Yasushi Yagi
yagi@am.sanken.osaka-u.ac.jp

[1] Ritsumeikan University, Shiga, Japan

[2] Hiroshima City University, Hiroshima, Japan

[3] Osaka University, Osaka, Japan

chest under several walking conditions (McDonald et al. 1983; Grasso et al. 1996; Moore et al. 2001; Grasso et al. 1998; Imai et al. 2001). These articles have shown that the eyes and head move cooperatively when walking straight McDonald et al. (1983), walking in circles Grasso et al. (1996), walking on a treadmill Moore et al. (2001), and walking and turning (Grasso et al. 1998; Imai et al. 2001), and that there is some coordination between the movement of the eyes and head while walking so that gaze direction is stabilized. In addition, coordination between the head and chest during walking has also been analyzed (Kavanagh et al. 2005, 2006). Kavanagh et al. (2005) analyzed the oscillatory dynamics of the head and trunk during walking and showed that the oscillations of the head were minimized by the cooperative trunk motions. They also showed that the trunk has a role in maintaining head stability during walking Kavanagh et al. (2006).

Based on the above-mentioned research, two types of coordination among the eyes, head and chest can occur in the following two situations: during large gaze reorientation, and during walking. Thus, some researchers have analyzed the movements of the eyes, head and chest in scenes in which both types of coordination mentioned above can be observed (Land 2004; Einhauser et al. 2007; Cinelli et al. 2007). Land (2004) analyzed and compared the movements of the eyes, head and trunk in two situations: tea making (the trunk is free to move) and driving (the trunk is fixed). The experimental results showed that the relationships between the gaze saccade size and the head and trunk movements were linear in the tea-making situation. In addition, the head-in-space movements in both situations were very similar; however, the head-on-trunk (neck) movements were quite different. Einhauser et al. (2007) also analyzed movements of the eyes and head while participants were exploring various environments such as a forest and a station, and confirmed eye–head coordination for horizontal movements. Their research mainly focused on the velocities of the eye and head movements and did not focus on the directions of the eye and head. Cinelli et al. (2007) analyzed the involvement of the head and trunk during gaze reorientation while participants were standing and walking on a treadmill. The results of their analysis showed that the trunk had significant rotational contributions to reorienting gaze, and that the contributions of the head and trunk during treadmill walking were smaller than those during standing. In their research, the participants were instructed to reorient gaze from the front to the side directions.

In this paper, we analyze eye, head, and chest movements when participants are intentionally gazing at a certain object while walking. As we note above, existing studies have focused on coordination among the eyes, head and chest during visual search or during reorienting from the front to the various directions; however, constrained gaze positions and fixating a moving target have not been considered. The effects of the target motions on the movements of the eye, head and chest have also not been analyzed. Thus, to investigate these relationships, we performed experiments in both walking and non-walking conditions, with various gaze target movements and compared the experimental results.

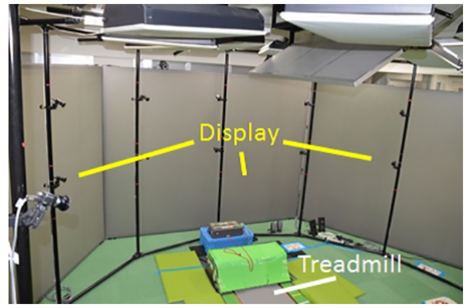

Fig. 1 Immersive walking environment

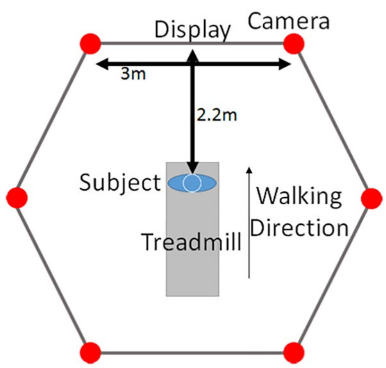

Fig. 2 Experimental setup

Experimental setup

Our experimental environment consisted of a treadmill surrounded by multiple screens and projectors (Fig. 1). Figure 2 shows the size of the environment. We prepared three experimental conditions as shown in Figs. 4, 5, and 6. In Experiments 1 and 2, the gaze target was fixed or moved at a constant angular velocity. In Experiment 3, the target was fixed on the virtual environment and moved along the walking path. In the walking conditions of Experiments 1 and 2 and all the conditions of Experiment 3, each participant walked on the treadmill while gazing at the target object projected on the screens. In the remaining conditions, the participant stood on the treadmill and gazed at the target. In the walking condition, each participant walked on the treadmill while gazing at the target object projected on the screens.

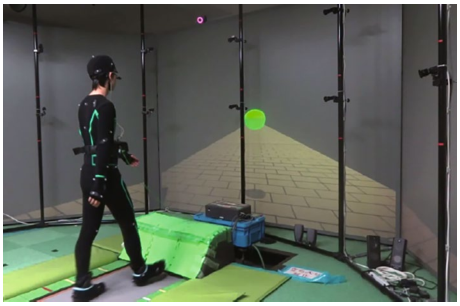

Fig. 3 Example of virtual space view and participant

Figure 3 shows an example of the virtual space and the gaze target (40-cm diameter, green sphere, 7.6° × 7.6° of visual angles from the participant in Experiment 1 and 2). Here, since the distances from the participant to the gaze target in the virtual space exceeds 10 m in Experiment 3, the size of the target was set so that the participant can gaze at the target even in such cases. The gaze target positions were changed depending on the experimental condition. In our experiment, both the gaze target and a corridor-like virtual space were shown on multiple screens, and the virtual space changed depending on the treadmill speed to make the participant feel as if they were actually walking in the space. (1–1) In this experiment, we employed Processing (version 1.5.1) to construct the virtual space and generate the participant's viewpoint images projected onto the screens.

In this paper, we considered situations in which people intentionally gazed at surrounding objects while walking. Although there are many possible movements of gaze target surrounding people, here we considered only two simple conditions of gaze target motion as shown in Figs. 4, 5 and 6 and analyzed the relationships between the eye, head, and chest movements.

In Experiment 1, the gaze directions were fixed (Fig. 4). This means that the target was located at relatively constant position to the participant, which would occur when it moves to the same direction and with the same speed as him/her. In Experiment 2, the gaze target moved at a constant angular velocity keeping the distance from the participant. Though the situations where the gaze target was fixed or moved at a constant angular velocity were very simple, but these experimental setups were performed to analyze the relationship between eye, head, and body movements precisely. In Experiment 3, on the other hand, we consider more complex gaze target movements. The target was fixed on the environment, or the target moved along the participants' walking path. Throughout this experiment, we aimed to evaluate the effects of gaze target movement. We obtained data in both walking and non-walking conditions to analyze the influence of walking on the eye, head and chest movements.

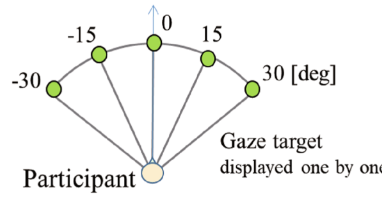

Fig. 4 Experiment 1

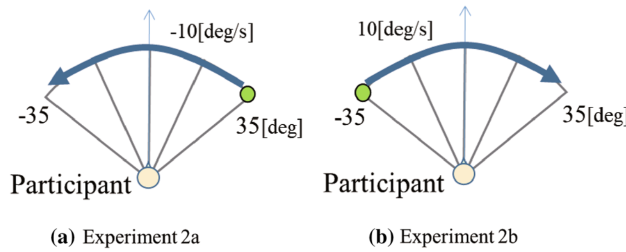

Fig. 5 Experiment 2

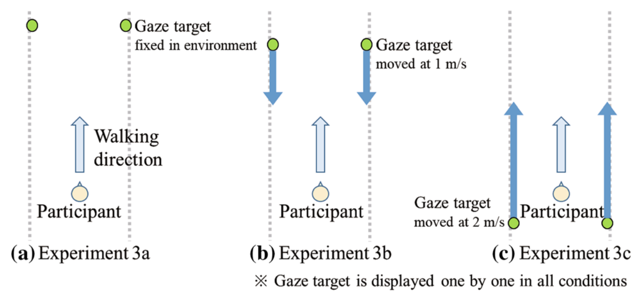

Fig. 6 Experiment 3 (overviews of whole virtual environments. Participants watched their viewpoint images generated based on their virtual positions, (1–2), dashed lines denote invisible walls that were not shown on screens)

Six cameras for motion capture system (Bonita 10, Vicon Motion Systems Ltd., UK) were located around the environment (Fig. 2). Using the motion capture system, we could obtain all body positions and poses including those of the head and chest. Gaze direction was measured by a wearable eye tracker (EMR-9, NAC Image Technology Inc., Japan). To integrate data obtained by the eye tracker and the motion capture system, we needed to calibrate them. Here, the eye tracker consisted of two eye cameras for observing eyes and one view camera for capturing the participants view images, and the outputs of the eye tracker are 2D positions in the view camera images. In addition, the direction of the view camera did not match accurately with the frontal direction of the participant's head. Thus, in the calibration, we need to estimate the relative relationship between the view camera and the head direction for obtaining the integrated data. A chessboard was first displayed on the screens and more than three images were captured by the view camera of the eye tracker. Based on these images, we can estimate the poses and positions of the view camera. At the same time, the poses and positions of the participant's head were acquired by the motion capture system at the timings of capturing images by the view camera. With the above information, we can estimate the relative relationship between the view camera and the head direction. The details of the calibration are given in Okada et al. (2013)

Experiment 1

In the Experiment 1, the participant gazed at a static target while walking, and we analyzed their eye, head, and chest movements. We compared the movements in walking and non-walking conditions.

Conditions

In Experiment 1, we consider five conditions of target directions (– 30°, – 15°, 0°, 15°, and 30°) as shown in Fig. 4. The target positions were calculated assuming that each participant stood 220 cm from the front screen (Fig. 2), so the actual target directions from the participant were slightly different depending on their actual position while walking. The participant was instructed to gaze at the target during the experiment. The gaze target was projected on each direction for 7.2 s. Until the gaze target was projected, we instructed the participant to gaze at the frontal direction. The order of the projected directions were counter-balanced across the participants. One trial consisted of five gaze directions, and each participant performed four trials in total.

Before the experiment, the participant walked on the treadmill for 5 min to get used to it. Throughout this procedure, the speed of the treadmill was set to the participant's comfortable walking speed and this treadmill speed was used in the walking condition. In the walking condition, the participant walked on the treadmill while gazing at the target. In the non-walking condition, the participant stood at the designated position (Fig. 2) while gazing at the target. We instructed the participants to stand with their toes pointed forward and not to move their feet during the non-walking condition for proper comparison between the walking and non-walking conditions. Each participant first performed the walking condition, followed by the non-walking condition. To reduce the effects of fatigue, each participant took a 3-min break after each trial in the walking condition, and a more than 5-min break between the walking and non-walking conditions.

Preprocessing

We conducted experiments with 14 male participants whose ages ranged from 21 to 24. However, since the captured data of three participants are missing, we employ 11 participants' data for the following analysis. Oral informed consent was obtained from all the participants. In the experiment, we captured their eye, head, and chest directions. These directions are defined as the angles between the walking direction and the eye, head, and chest directions while walking and between the front direction and the body directions while not walking as shown in Fig. 7. We also defined the eye-in-orbit, head-on-chest and chest-in-space angles. We analyze the relationship between the gaze direction and the eye-in-orbit, head-on-chest and chest-in-space.

Figure 8 shows example target direction and gaze, head and chest directions captured in the experiment. In this experiment, the gaze target was projected in one direction for 7.2 s and disappeared afterwards. Then, the target was projected in the next direction. The thick lines denote the timings of the target appearances. Here, we can see transition phases after the target appearances particularly in the eye direction results. To remove the effects of these transition phases, we excluded a certain period after the target appeared from the analysis, and used only the stable period. From observing the captured data, we experimentally determined the durations of (1–3) the transition phases to be 3 s (gray periods in Fig. 8), and excluded these periods from the analysis. As a result, the remaining 4.2 s were used for analysis.

Results

Figure 9 shows the relationships between gaze and eye-in-orbit (Ex1Ew), between gaze and head-on-chest (Ex1Hw) and between gaze and chest-in-space angles (Ex1Cw) while walking, and Fig. 10 shows these in the non-walking conditions (Ex1Enw, Ex1Hnw, Ex1Cnw). The horizontal axes denote the gaze directions and the

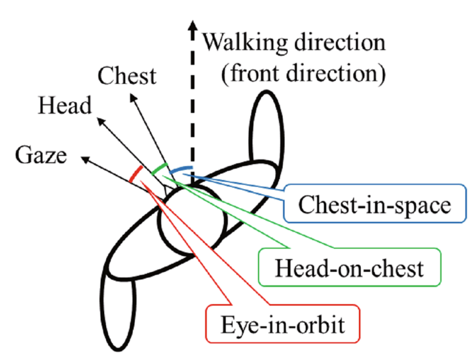

Fig. 7 Definitions of gaze, head, and chest directions

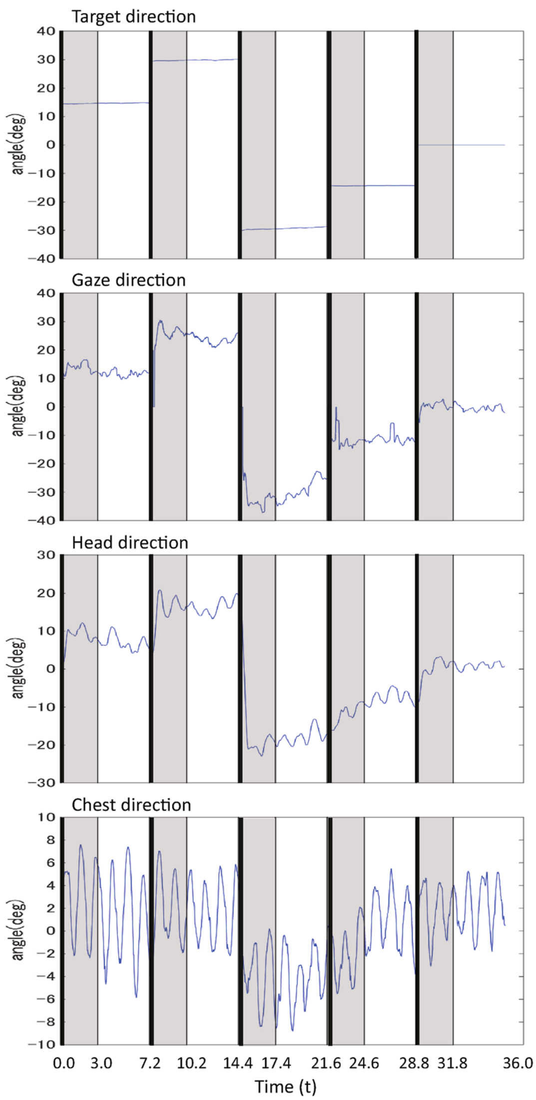

Fig. 8 Analyzed data (example of one participant in Experiment 1, gray periods are (1–3) transition phases that are excluded from analysis)

vertical axes denote the eye-in-orbit, head-on-chest or chest-in-space angles. In these graphs, the obtained data of all participants and the mixed-effects regression results (the red lines) are shown. Table 1 shows the mixed-effects regression results and their marginal R-squared.

Figures 9 and 10, and Table 1 show that the gaze and the eye-in-orbit, the gaze and the head-on-chest and the gaze and the chest-in-space have linear relationships not only in the non-walking conditions but also in the walking conditions, i.e., the eye-in-orbit, head-on-chest and chest-in-space face right (left) when the participant gazes at their right (left) side. Table 1 shows that R-squared values of Ex1Ew, Ex1Hw, Ex1Hnw and Ex1Hnw are high, and R-squared values of Ex1Cw and Ex1Cnw are low. This means that the eye-in-orbit and head-on-chest angles have higher correlations with the gaze directions than the chest-in-space angles.

We conducted a linear mixed-effects regression analysis to determine whether the participant gait is affected by walking. Here, we employ a dummy variable to indicate the walking conditions (non-walking:0, walking:1). Tables 2 shows the analysis results. Here, the factors we are interested in are Gaze:Walking, the interaction between gaze direction and walking condition. From the analysis results, we can confirm the significant differences in chest-in-space ($p = 0.009$).

From these analysis, we confirmed that the gaze and the eye-in-orbit, the gaze and the head-on-chest, and the gaze and the chest-in-space have linear relationships in both walking and non-walking conditions. We also confirmed that the slopes of the chest-in-space are decreased by walking. (1–4) This means that the movements of the chest-in-space can be affected by walking, although the changes are small.

Experiment 2

In Experiment 1, we considered only a static target and the target directions from the participants did not change with time. If the gaze target moves and the directions change continuously, the eye, head, and, chest movements can change even when the target angle is the same. Therefore, in Experiment 2, we considered situations where the target moves and analyzed the relationship of the head and chest with the gaze directions.

Although the target directions relative to the participant can be changed in a complex fashion when humans are

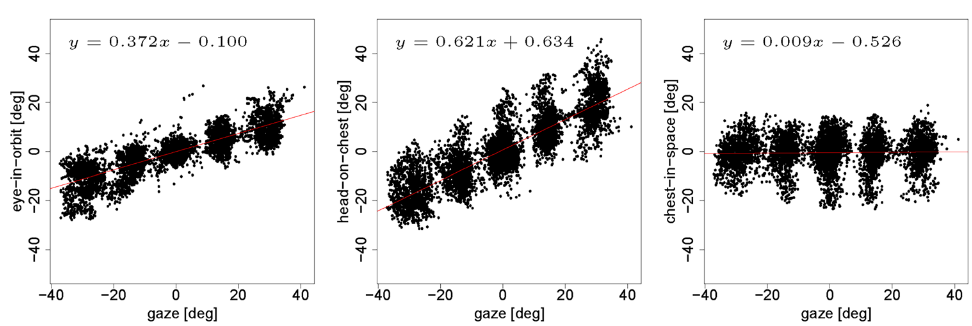

Fig. 9 Relationships between gaze and eye-in-orbit (Ex1Ew,left), head-on-chest (Ex1Hw,center) and chest-in-space (Ex1Cw,right) in walking

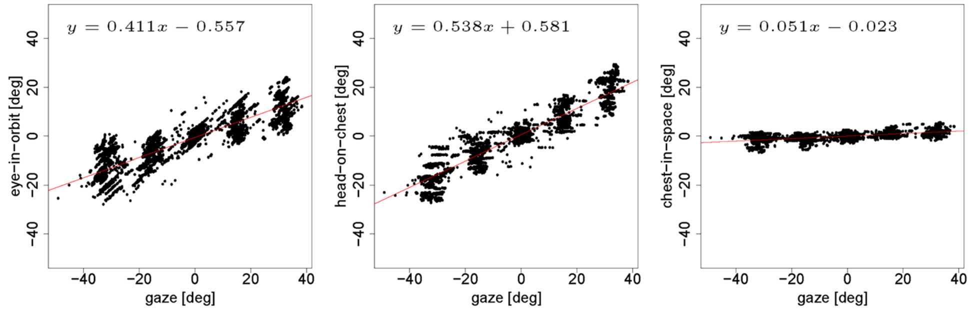

Fig. 10 Relationships between gaze and eye-in-orbit (Ex1Enw,left),head-on-chest (Ex1Hnw,right) and chest-in-space (Ex1Cnw,right) in non-walking

Table 1 Regression equations and adjusted R-squared (Experiment 1)

	Regression equation	Marginal R^2
Ex1Ew	$0.372x - 0.100$	0.712
Ex1Hw	$0.621x + 0.634$	0.745
Ex1Cw	$0.009x - 0.526$	0.001
Ex1Enw	$0.411x - 0.557$	0.760
Ex1Hnw	$0.538x + 0.581$	0.852
Ex1Cnw	$0.051x - 0.023$	0.388

Table 2 Regression analysis results of Experiment 1

	Estimate	SD	t value	p value
Eye-in-orbit				
(Intercept)	− 0.517	0.343	− 1.507	0.164
Gaze	0.413	0.059	7.024	< 0.001***
Walking	0.418	0.467	0.896	0.392
Gaze:Walking	− 0.042	0.062	− 0.673	0.515
Head-on-chest				
(Intercept)	0.558	0.377	1.480	0.171
Gaze	0.540	0.056	9.577	< 0.001***
Walking	0.074	0.705	0.105	0.919
Gaze:Walking	0.081	0.055	1.483	0.168
Chest-in-space				
(Intercept)	− 0.033	0.140	− 0.233	0.821
Gaze	0.050	0.011	4.757	< 0.001***
Walking	− 0.497	0.473	− 1.052	0.315
Gaze:Walking	− 0.042	0.013	− 3.128	0.009**

$\cdot p < 0.1$, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$

walking and gazing at an object, we consider only constant velocity movements to precisely evaluate the effects of the gaze target motion.

Conditions

The experimental conditions were the same as in Experiment 1 except for the gaze target movement. The target moved between $\pm 35°$, and its angular velocity was $\pm 10[°/s]$ as shown in Fig. 5. First, the target appeared at the start position ($-35°$ or $35°$) for 2 s. After that, the target moved for 7 s at the designated speed. Experiments 2a and 2b correspond with conditions where the target moves from right to left, and from left to right, respectively (Fig. 5). The same participants as in Experiment 1 took part in this experiment and the participants performed three trials for each experiment.

Results

Figures 11 and 12 show the relationship between the gaze and the eye-in-orbit (Ex2aEw, Ex2aEnw), between the gaze and the head-on-chest (Ex2aHw, Ex2aHnw), and between the gaze and the chest-in-space (Ex2aCw, Ex2aCnw) in Experiment 2a. Figures 13 and 14 show the same data from Experiment 2b (called Ex2bEw, Ex2bEnw, Ex2bHw, Ex2bHnw, Ex2bCw, and Ex2bCnw), The horizontal axes denote the gaze directions and the vertical axes denote the eye-in-orbit, head-on-chest or chest-in-space angles. In

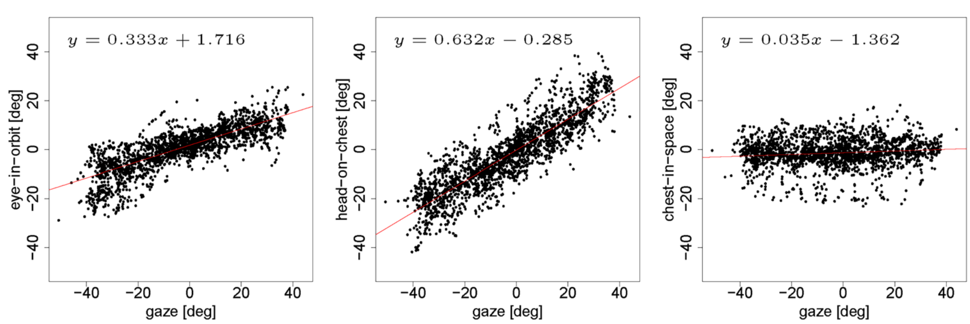

Fig. 11 Relationships between gaze and eye-in-orbit (Ex2aEw,left),head-on-chest (Ex2aHw,right) and chest-in-space (Ex2aCw,right) in walking

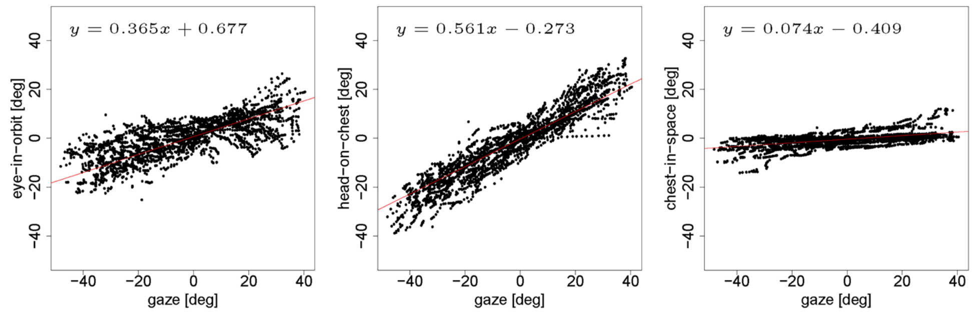

Fig. 12 Relationships between gaze and eye-in-orbit (Ex2aEnw,left),head-on-chest (Ex2aHnw,right) and chest-in-space (Ex2aCnw,right) in non-walking

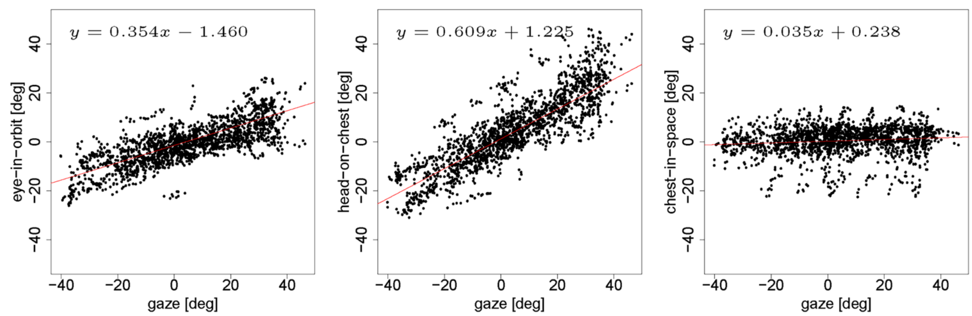

Fig. 13 Relationships between gaze and eye-in-orbit (Ex2bEw,left),head-on-chest (Ex2bHw,right) and chest-in-space (Ex2bCw,right) in walking

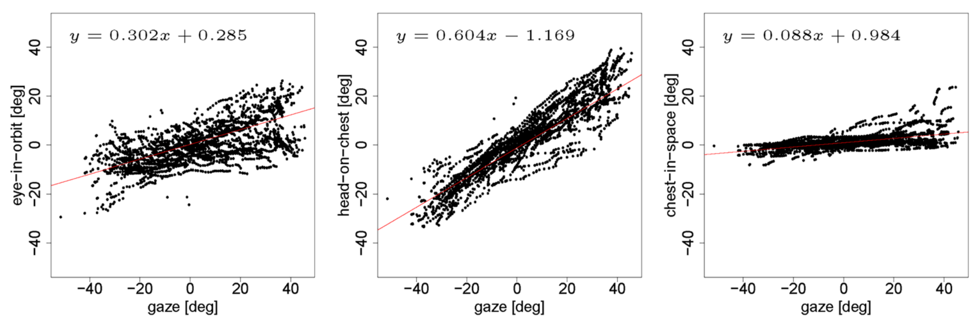

Fig. 14 Relationships between gaze and eye-in-orbit (Ex2bEw,left),head-on-chest (Ex2bHw,right) and chest-in-space (Ex2bCw,right) in walking

Table 3 Regression equations and adjusted *R*-squared (Experiment 2a)

	Regression equation	Marginal R^2
Ex2aEw	$0.333x + 1.716$	0.661
Ex2aHw	$0.632x - 0.285$	0.782
Ex2aCw	$0.035x - 1.362$	0.015
Ex2aEnw	$0.365x + 0.677$	0.599
Ex2aHnw	$0.561x - 0.273$	0.795
Ex2aCnw	$0.074x - 0.409$	0.292

Table 4 Regression equations and adjusted *R*-squared (Experiment 2b)

	Regression equation	Marginal R^2
Ex2bEw	$0.354x - 1.460$	0.568
Ex2bHw	$0.609x + 1.225$	0.678
Ex2bCw	$0.035x + 0.238$	0.013
Ex2bEnw	$0.302x + 0.285$	0.458
Ex2bHnw	$0.604x - 1.169$	0.798
Ex2bCnw	$0.088x + 0.984$	0.300

these graphs, the obtained data are shown and the red lines show the mixed-effects regression results. Tables 3 and 4 show the mixed-effects regression results and their marginal *R*-squared.

Figures 11, 12, 13, 14, and Tables 3 and 4 show similar tendencies as that of Experiment 1. The gaze and the eye-in-orbit, the gaze and the head-on-chest and gaze and the chest-in-space have also linear relationships in both the walking and the non-walking conditions. From Tables 3 and 4, the eye-in-orbit and head-on-chest angles have higher correlations with the gaze directions than the chest-in-space angles have. Comparing the walking and non-walking results, the *R*-squared of head-on-chest and chest-in-space in walking are smaller than the ones in non-walking, however, the *R*-squared of eye-in-orbit in walking is not smaller than the one in non-walking.

Table 5 Regression analysis results of Experiment 2a

	Estimate	SD	*t* value	*p* value
Eye-in-orbit				
(Intercept)	0.942	0.874	1.079	0.313
Gaze	0.394	0.076	5.177	< 0.001***
Walking	0.743	0.841	0.883	0.401
Gaze:Walking	− 0.062	0.065	− 0.955	0.368
Head-on-chest				
(Intercept)	− 0.400	0.712	− 0.562	0.588
Gaze	0.538	0.067	8.064	< 0.001***
Walking	0.161	0.710	0.227	0.826
Gaze:Walking	0.096	0.057	1.694	0.132
Chest-in-space				
(Intercept)	− 0.536	0.314	− 1.705	0.127
Gaze	0.079	0.021	3.668	0.006**
Walking	− 0.841	0.623	− 1.348	0.204
Gaze:Walking	− 0.043	0.028	− 1.543	0.159

·$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 6 Regression analysis results of Experiment 2b

	Estimate	SD	*t* value	*p* value
Eye-in-orbit				
(Intercept)	0.748	1.409	0.531	0.607
Gaze	0.296	0.060	4.934	< 0.001***
Walking	− 2.147	1.162	− 1.848	0.094·
Gaze:Walking	0.055	0.030	1.837	0.105
Head-on-chest				
(Intercept)	− 1.309	1.287	− 1.017	0.333
Gaze	0.589	0.050	11.685	< 0.001***
Walking	2.448	1.582	1.547	0.155
Gaze:Walking	0.028	0.014	1.938	0.093·
Chest-in-space				
(Intercept)	0.870	0.368	2.366	0.044*
Gaze	0.085	0.022	3.923	0.003**
Walking	− 0.619	0.937	− 0.660	0.524
Gaze:Walking	− 0.052	0.023	− 2.285	0.051·

·$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

We conducted a mixed-effects regression analysis to determine whether the participant gait is affected by walking. Here, walking conditions were transformed into a dummy variable (non-walking, 0; walking, 1) Tables 5 and 6 show the analysis results of Experiments 2a and 2b, respectively. Here, we also focus on Gaze:Walking, the interaction between gaze direction and walking condition. From the analysis results, although we cannot confirm the significant differences in Experiment 2a, we can obtain significant tendencies in head-on-chest ($p = 0.093$) and chest-in-space ($p = 0.051$).

From these results, we confirmed that the gaze and the eye-in-orbit, the gaze and the head-on-chest, and the gaze and the chest-in-space also have linear relationships in both walking and non-walking conditions. (1–5) We also confirmed that the significant tendencies of interaction between gaze and walking (Gaze:Walking) in the head-on-chest and chest-in-space, this means the head-on-chest and chest-in-space movements can be affected by walking although these changes will be small.

Experiment 3

In Experiments 1 and 2, we analyzed participants' eye, head, and chest movements while they gazed at a static target (Experiment 1) or a target moving at a constant angular velocity (Experiment 2) while walking or non-walking. However, such situations do not occur in natural scenes. Thus, in Experiment 3, we focused on more complex target movements. As shown in Fig. 6, the target was fixed in the environment or moved along the participants' walking path. Figure 6 shows the complete virtual environment; the virtual environment from the participants' perspective was displayed according to the participant's virtual positions.

Conditions

The experimental conditions were the same as in Experiments 1 and 2 except for the gaze target's movement. An overview of Experiment 3 is shown in Fig. 6. In Experiment 3a, the gaze target was fixed on the left or right wall 10 m from the participant's initial position. In Experiment 3b, the target appeared on the left or right wall 12 m from the participant's initial position and moved along the wall at 1 m/s in the inverse direction of the participant's walk. In Experiment 3c, the target appeared on the left or right wall 2 m from the participant and moved along the wall at 2 m/s in the same direction as the participant's walk. (1–2) Here, note that the walls were not displayed on the screens, and only the target was displayed. The range of the target's speed was 0.6–8.8°/s in Experiment 3a, 1.0–19.5°/s in Experiment 3b, and 0.2–16.1°/s in Experiment 3c. (1–1) Unlike Experiments 1 and 2, in Experiment 3, the distance between the participant and the target in the virtual space changes. Thus, the angular size of the target from the participant's viewpoint also changes.

Each experiment continued until the participant walked 12 m. The same participants as in Experiments 1 and 2 took part in this experiment, and the participants performed four trials for each experiment. As described above, Experiments 3a, 3b and 3c consisted of two conditions in which the target

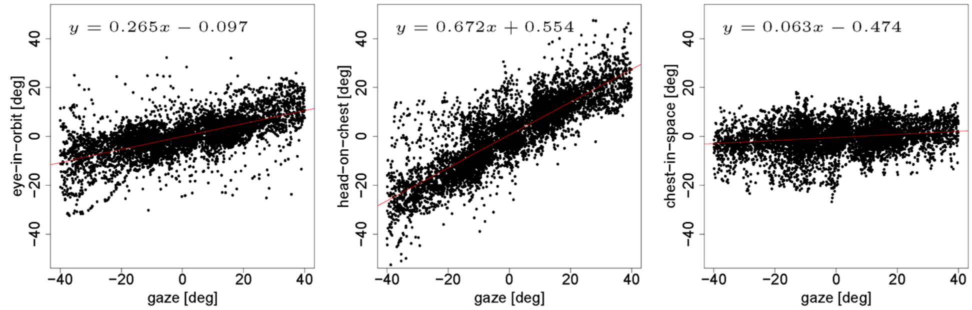

Fig. 15 Relationships between gaze and eye-in-orbit (Ex3aE,left), head-on-chest (Ex3aH,center) and chest-in-space (Ex3aC,right) in walking

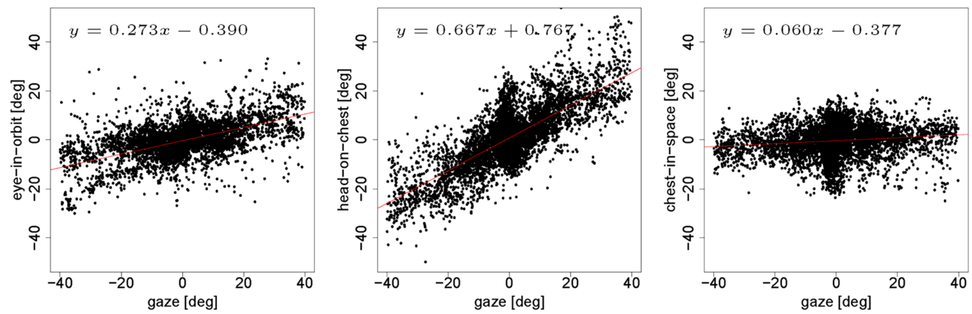

Fig. 16 Relationships between gaze and eye-in-orbit (Ex3bE,left), head-on-chest (Ex3bH,center) and chest-in-space (Ex3bC,right) in walking

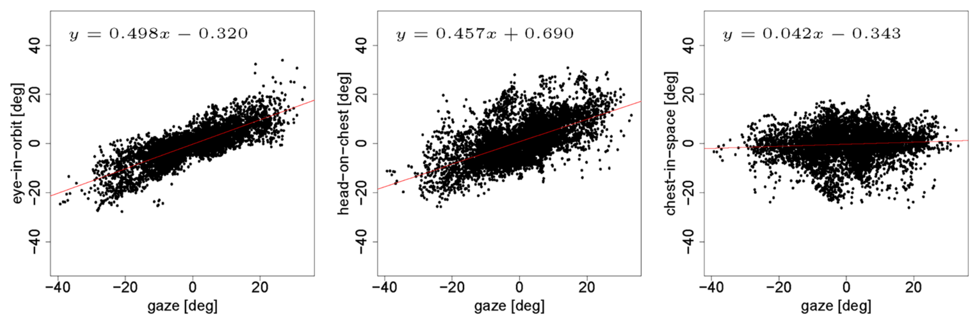

Fig. 17 Relationships between gaze and eye-in-orbit (Ex3cE,left), head-on-chest (Ex3cH,center) and chest-in-space (Ex3cC,right) in walking

was positioned on the left or right. Thus, the total number of trial numbers in Experiment 3 for one participant was 24.

Results

Figures 15, 16, 17 show the relationship between the gaze and the eye-in-orbit, between the gaze and the head-on-chest and between the gaze and the chest-in-space in Experiments 3a, 3b and 3c. The horizontal axes denote the gaze directions, and the vertical axes denote the eye-in-orbit, head-on-chest or chest-in-space angles. The obtained data are shown in these graphs, and the red lines indicate the mixed-effects regression results. Table 7 shows the mixed-effects regression results and their marginal *R*-squared.

Figures 15, 16, 17 show similar tendencies with Experiments 1 and 2. The gaze and the eye-in-orbit, the gaze and the head-on-chest and gaze and the chest-in-space also have linear relationships. Table 7 also shows similar tendencies: the eye-in-orbit and head-on-chest angles have higher correlations with gaze direction than the chest-in-space angle has.

Table 7 Regression equations and adjusted *R*-squared (Experiment 3)

	Regression equation	Marginal R^2
Ex3aE	$0.265x - 0.097$	0.427
Ex3aH	$0.672x + 0.554$	0.735
Ex3aC	$0.063x - 0.474$	0.040
Ex3bE	$0.273x - 0.390$	0.303
Ex3bH	$0.667x + 0.767$	0.568
Ex3bC	$0.060x - 0.377$	0.016
Ex3cE	$0.498x - 0.320$	0.660
Ex3cH	$0.457x + 0.690$	0.371
Ex3cC	$0.042x - 0.343$	0.005

Next, we compare the slopes of Experiment 3's regression result with those of Experiments 1 and 2. The target speeds in Experiments 1 and 2 were 0.0 and 10.0 [°/s], and the target speed ranges in Experiment 3 were 0.2–19.5 [°/s], as described above. Target speeds in Experiment 3 did not match those in Experiments 1 and 2 completely.

Thus, although we cannot compare the regression results directly, Experiments 3a and 3b's regression slopes were similar to those in Experiments 1 and 2. However, Experiment 3c's regression slopes were considerably different from the others.

From these results, we confirmed that we can obtain similar linear relationships between gaze directions and the eye-in-orbit, head-on-chest, and chest-in-space angles. We also confirmed that the regression slopes vary depending on the target's motion conditions.

Discussion

In this section, we discuss the experimental results from two perspectives: the relationship between gaze and body movements and the effects of walking on bodily motion.

Relationship between gaze and body movements

Based on all experimental results (Figs. 9, 10, 11, 12, 13, 14, 15, 16, 17), we confirmed that the eye-in-orbit, head-on-chest, and chest-in-space angles have linear relationships with gaze direction regardless of walking conditions and regardless of the target's movement.

The regression results (Tables 1, 3, 4 and 7) showed that the head-on-chest angle had strong correlations with gaze directions (≥ 0.5) except Ex3cH, and the eye-in-orbit angle had moderate or strong correlations with gaze directions (≥ 0.5) except Ex2bEnw, Ex3aE and Ex3bE in both the walking and non-walking conditions. However, the chest-in-space angle had weaker correlations with the gaze directions than the eye-in-orbit and the head-on-chest angles had.

We compared the marginal *R*-squared in the walking and non-walking conditions and found that walking essentially decreased the correlations (*R*-squared values) except with the eye-in-orbit angle in Experiment 2. Here, we assumed that body part vibrations caused by walking caused a decrease in correlation. To evaluate the vibration effects, we calculated the average directions during one gait cycle and conducted a robust regression using the averaged values in Experiment 1.

Figure 18 shows the relationships between the gaze and the averaged values of the eye-in-orbit (Ex1Ew_ave), head-on-chest (Ex1Hw_ave), and chest-in-space (Ex1Cw_ave) angles while walking. The red lines in the figure indicate the robust regression results. Table 8 shows the regression results and their marginal *R*-squared. The *R*-squared of Ex1Cw_ave is larger than the *R*-squared of Ex1Cw, but it is smaller than the *R*-squared of Ex1Cnw. These results suggest that only chest vibrations caused by walking do not decrease the correlation. On the other hand, the *R*-squared of Ex1Ew_ave and Ex1Hw_ave are also larger than the *R*-squared of Ex1Ew and Ex1Hw, and they are almost same as the values of Ex1Enw and Ex1Hnw. These results suggest that the decreased correlations in the eye-in-orbit and head-on-chest angles are mainly the result of vibrations caused by walking. However, the marginal *R*-squared of the eye-in-orbit angle in the walking condition is larger than those in the non-walking condition in Experiment 2. Thus, the results suggested that walking did not necessarily decrease eye-in-orbit angle correlations, and its effects on the correlation of the eye-in-orbit angle changed depending on the target's movements.

Existing research (Fang et al. 2015; Freedman 2008) has reported similar linear relationships between gaze and head directions. In these studies, the participants performed visual search tasks in non-walking (standing) situations. Cinelli 's research Cinelli et al. (2007) focused on the involvement of the head and trunk during gaze reorientation. Although they did not analyze linear relationships between gaze and other body parts, the results showed linear relationships between the gaze and eye-in-orbit, head-on-shoulders, shoulders-on-hips, and hips-on-space angles within the same gaze direction ranges. The participants conducted gaze reorientations in non-walking (standing) and treadmill walking situations.

Table 8 Regression equations and adjusted *R*-squared (Experiment 1 in walking)

	Regression equation	Marginal R^2
Ex1Ew_ave	$0.377x - 0.048$	0.744
Ex1Hw_ave	$0.581x + 0.175$	0.888
Ex1Cw_ave	$0.042x - 0.128$	0.159

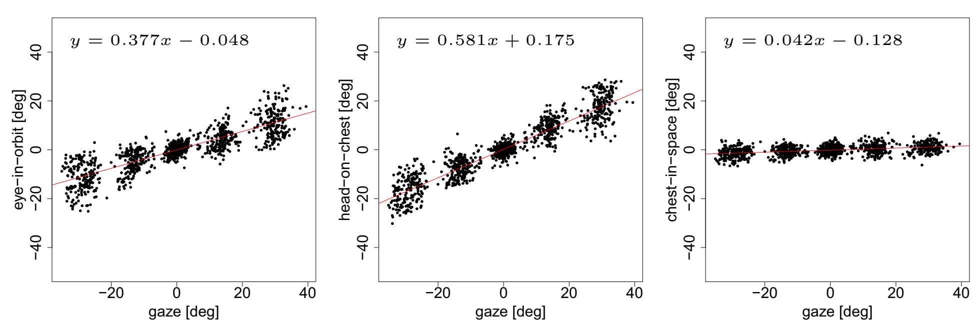

Fig. 18 Relationships between gaze and averaged values of eye-in-orbit, head-on-chest and chest-in-space (Ex1Ew_ave,Ex1Hw_ave,Ex1Cw_ave) in walking

These results indicate that a linear relationship may exist between gaze and body movements regardless of participants' gazing behaviors or tasks.

Effects of walking

Experiment 1's results showed that walking decreased rotational chest-in-space movements, and Experiment 2's results showed that walking decreased rotational chest-in-space movements and increased head-on-chest movements (only in Experiment 2b).

Cinelli's research Cinelli et al. (2007) identified similar tendencies, i.e., larger head rotations and smaller hip rotations during treadmill walking than standing when participants reoriented their gazes from the front to the side. These results suggest that rotational head and chest movements can be changed by walking regardless of gaze direction movement.

Next, we consider three possible causes for the above changes. The first is phase differences between chest and hip rotations. When humans walk, the head, chest and hip (pelvis) rotate, and pelvic rotations lengthen the step. These pelvic rotations are compensated by thoracic counterrotations. However, Bruijn et al. (2008) reported that phase differences between pelvic and thoracic rotations change when walking speed increases. This means that the pelvis and thorax do not necessarily counterrotate. One possible cause of decreased chest rotations is gaze direction change, which may cause changes in the phase differences between pelvic and thoracic rotations.

The second possible cause is arm swing. Bruijn et al. (2010) also reported that arms and legs have larger contributions to total body angular momentum. In our previous study, we analyzed the relationship between gaze direction and arm swing amplitudes, and we confirmed the tendency for decreased swing amplitude in the arm further from the gaze direction and increased swing amplitude in the arm closer to the gaze direction Yamazoe et al. (2017). Such changes in arm swing amplitudes can cause decreased chest rotation.

The third possible cause is trajectory change caused by head rotation. Many researchers have analyzed the relationship between gaze direction and walking trajectories (Jahn et al. 2006; Bernardin et al. 2012). Jahn et al., reported that head rotation to one side caused a gait deviation to the opposite side. Bernardin et al. reported that gaze direction anticipates head orientation, and head orientation anticipates the reorientation of other body segments. (0) Neck proprioceptive inputs can also affect gait. Neck muscle vibration induces a deviation in head direction when stepping in place Ivanenko et al. (2000). Based on these research, head direction and walking direction and trajectories have strong relationships. However, we cannot change walking direction on the treadmill. Thus, to compensate for such changes in walking directions, chest rotations might decrease.

Next, we discuss Experiment 3's results. As described in "Result", Experiment 3's gaze target velocity ranges were similar to those in Experiments 1 and 2. However, the slopes of Experiment 3c differed considerably. We focused on temporal changes to the target velocities, so the target in Experiments 3a and 3b first moved slowly, and its velocity gradually increased. In Experiment 3c, the target first moved quickly, and its velocity gradually decreased. These results suggest that not only the target velocity itself, but also its temporal changes, may affect the relationship between body rotation and gaze direction.

Conclusion

In this paper, we analyzed the relationship between eye-in-orbit, head-on-chest, and chest-in-space movements with gaze directions in walking and non-walking conditions, and conducted three situations: fixed gaze target (Experiment 1) and moving gaze target (Experiment 2), and gaze target with realistic movements (Experiment 3).

From the experimental results, we confirmed (1) linear relationships between the eye-in-orbit, head-on-chest, and chest-in-space angles with gaze directions regardless of walking, non-walking, and target movements; (2) head-on-chest had stronger correlations with gaze direction than eye-in-orbit and chest-in-space had; (3) effects of walking that constrain rotational body movements; (4) parts with larger moments are more easily affected by walking; and (5) not only the target velocity itself but also its temporal changes may affect the relationship between body rotational movements with the gaze directions. In addition, our results and those of existing studies also show the possibility of the existence of linear relationships between the gaze, head and chest directions regardless of walking, non-walking situations, or the participant's gaze behavior.

Future work includes experiments in which the gaze target is placed across a wider area of space to evaluate the behaviors of participants who gaze over larger areas. We are also investigating changes in the relationships between gaze and body movements when participants conduct different visual tasks such as visual search tasks.

Acknowledgements This study was supported by the JST CREST "Behavior Understanding based on Intention-Gait Model" project.

References

Anastasopoulos D, Ziavra N, Hollands M, Bronstein A (2009) Gaze displacement and inter-segmental coordination during large whole body voluntary rotations. Exp Brain Res 193:323–336

Anastasopoulos D, Naushahi J, Sklavos S, Bronstein AM (2015) Fast gaze reorientations by combined movements of the eye, head, trunk and lower extremities. Exp Brain Res 233:1639–1650

Barnes G (1979) Vestibulo-ocular function during co-ordinated head and eye movements to acquire visual targets. J Psychol 287:127–147

Bernardin D, Kadone H, Bennequin D, Sugar T, Zaoui M, Berthoz A (2012) Gaze anticipation during human locomotion. Exp Brain Res 223(1):65–78

Bruijn SM, Meijer OG, Beek PJ, van Dieën JH (2010) The effects of arm swing on human gait stability. J Exp Biol 213(23):3945–3952

Bruijn SM, Meijer OG, Van Dieen JH, Kingma I, Lamoth CJ (2008) Coordination of leg swing, thorax rotations, and pelvis rotations during gait: the organisation of total body angular momentum. Gait Posture 27(3):455–462

Cinelli M, Patla A, Stuart B (2007) Involvement of the head and trunk during gaze reorientation during standing and treadmill walking. Exp Brain Res 181:183–191

Einhauser W, Schumann F, Bardins S, Bartl K, Boning G, Schneider E, Konig P (2007) Human eye-head co-ordination in natural exploration. Netw Comput Neural Syst 18(3):267–297

Fang Y, Nakashima R, Matsumiya K, Kuriki I, Shioiri S (2015) Eye-head coordination for visual cognitive processing. PLoS One 10:3

Freedman EG (2008) Coordination of the eyes and head during visual orienting. Exp Brain Res 190:369–387

Freedman EG, Sparks DL (2000) Coordination of the eyes and head: movement kinematics. Exp Brain Res 131:22–32

Grasso R, Glasauer S, Takei Y, Berthoz A (1996) The predictive brain: anticipatory control of head direction for the steering of locomotion. NeuroReport 7(6):1170–1174

Grasso R, Prevost P, Ivanenko YP, Berthoz A (1998) Eye-head coordination for the steering of locomotion in humans: an anticipatory synergy. Neurosci Lett 253(2):115–118

Imai T, Moore ST, Raphan T (2001) Interaction of the body, head and eyes during walking and turning. Exp Brain Res 136:1–18

Ivanenko YP, Grasso R, Lacquaniti F (2000) Neck muscle vibration makes walking humans accelerate in the direction of gaze. J Physiol 525(3):803–814

Jahn K, Kalla R, Karg S, Strupp M, Brandt T (2006) Eccentric eye and head positions in darkness induce deviation from the intended path. Exp Brain Res 174(1):152–157

Kavanagh J, Barrett R, Morrison S (2006) The role of the neck and trunk in facilitating head stability during walking. Exp Brain Res 172:454–463

Kavanagh J, Morrison S, Barrett R (2005) Coordination of head and trunk accelerations during walking. Eur J Appl Physiol 94(4):468–475

Land MF (2004) The coordination of rotations of the eyes, head and trunk in saccadic turns produced in natural situations. Exp Brain Res 159:2

McDonald J, Bahill A, Friedman M (1983) An adaptive control model for human head and eye movements while walking. IEEE Trans Syst Man Cybern 13(2):167–174

Moore ST, Hirasaki E, Raphan T, Cohen B (2001) The human vestibulo-ocular reflex during linear locomotion. Ann N Y Acad Sci 942:139–147

Okada T, Yamazoe H, Mitsugami I, Yagi Y (2013) Preliminary analysis of gait changes that correspond to gaze directions. In: International joint workshop on advanced sensing/visual attention and interaction (ASVAI), pp 788–792

Oommen BS, Smith RM, Stahl JS (2004) The influence of future gaze orientation upon eye-head coupling during saccades. Exp Brain Res 155(1):9–18

Sklavos S, Anastasopoulos D, Bronstein A (2010) Kinematic redundancy and variance of eye, head and trunk displacements during large horizontal gaze reorientations in standing humans. Exp Brain Res 202:879–890

Stahl JS (1999) Amplitude of human head movements associated with horizontal saccades. Exp Brain Res 126:41–54

Thumser Z, Oommen B, Kofman I, Stahl J (2008) Idiosyncratic variations in eye-head coupling observed in the laboratory also manifest during spontaneous behavior in a natural setting. Exp Brain Res 191:419–434

Yamazoe H, Mitsugami I, Okada T, Echigo T, Yagi Y (2017) Immersive walking environment for analyzing gaze-gait relations. Trans Virtual Real Soc Jpn 22(3):435–443

Zangemeister W, Stark L (1982) Types of gaze movement: variable interactions of eye and head movements. Exp Neurol 77:563–577

Zangemeister WH, Stark L (1982) Gaze latency: Variable interactions of head and eye latency. Exp Neurol 75:389–406

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.